DOE/OE Transmission Reliability Program

Application of VARPRO Ambient Mode Estimation

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VAPRO Project Summary

- **Overall project objective**

  Detect and Analyze Oscillations in Power System Data

- **Looking Back:**
  - Ringdown VARPRO: Tech Transfer to PowerWorld
  - Ringdown VARPRO: CERTS Tool Available/Matlab
  - Ringdown VARPRO: Routinely used by BPA Engineers
  - Ambient VARPRO: Introduced a method for application of VARPRO to Ambient Data analysis.
  - Ambient VARPRO: Initial Studies on brake data demonstrate promise.

- **Publications:**
  - Borden, A.R., Lesieutre, B.C.; "Variable Projection Method for Power System Modal Identification," *IEEE Transactions on Power Systems*, Vol. 29, No. 6, pp. 2613-2620, November 2014.
  - Lesieutre, B.C., "Application of VARPRO to Ambient Mode Estimation" draft report prepared. Final report August 2015.

Topics to Address

- **Looking Forward:**
  - Apply method to new data datasets.
  - Develop additions to assess the quality of estimates (error bars).
  - Implement algorithms in BPA facility

  - Risk Factors: Data Availability

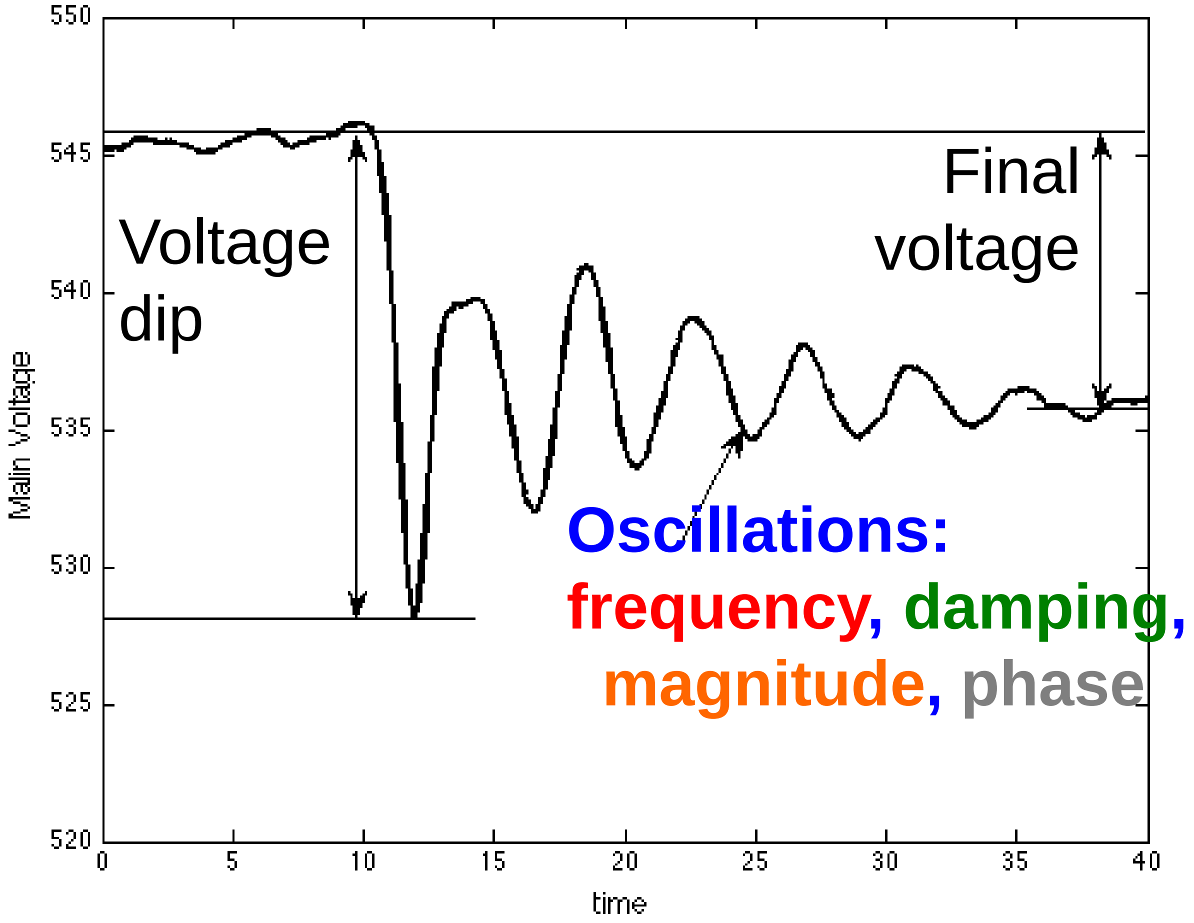
Presentation:

Review VAPRO Algorithm for Analysis of Oscillations

Present Approach to analyze ambient data

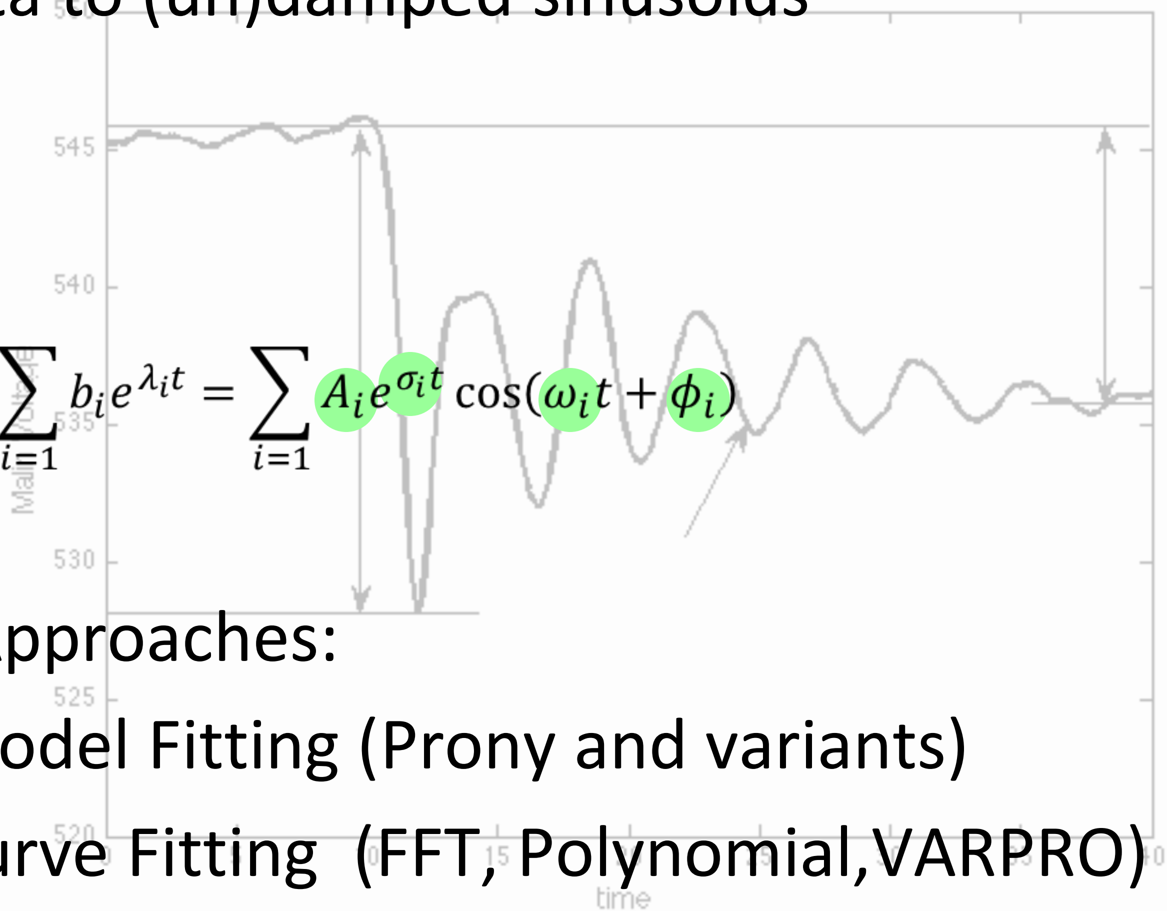
Present initial results of analysis of ambient data

Review: Ringdown Analysis



Review: Ringdown Analysis

- Fit data to (un)damped sinusoids



$$x(t) \approx \sum_{i=1} b_i e^{\lambda_i t} = \sum_{i=1} A_i e^{\sigma_i t} \cos(\omega_i t + \phi_i)$$

- Two Approaches:

  Model Fitting (Prony and variants)

  Curve Fitting (FFT, Polynomial,VARPRO)

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Review: Model Fitting

Many approaches use a three-stage process:

1. Use correlations in data to **construct a linear system model.** $y[n] = \alpha_1 y[n-1] + \cdots + \alpha_N y[n-N]$
2. Calculate natural modes of model. Roots of

$$0 = -z^N + \alpha_1 z^{N-1} + \cdots + \alpha_N$$

1. Calculate corresponding coefficients to match data.

$$y[n] = r_1 z_1^n + \cdots + r_N z_N^n$$

Advantage: Each step involves a **FAST** linear calculation.

Disadvantage: It is not curve fitting, and it has issues…

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Curve Fitting

Fit data to (un)damped sinusoids

- Frequency ω_i $\left[\frac{rad}{sec}\right]$
- Damping σ_i $\left[\frac{rad}{sec}\right]$

Mode Shapes

- Amplitude A_i
- Phase ϕ_i $[rad]$

$$x(t) \approx \sum_{i=1} b_i e^{\lambda_i t} = \sum_{i=1} A_i e^{\sigma_i t} \cos(\omega_i t + \phi_i)$$

$$\min_{A_i,\ \sigma_i,\ \omega_i,\ \phi_i} \left\| x(t) - \sum_i A_i e^{\sigma_i t} \cos(\omega_i t + \phi_i) \right\|_2$$

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Curve Fitting: Nonlinear Method

$$\alpha = [\alpha_1 , \dots , \alpha_p]$$ *Optimization variables (damping & frequencies)*

$$\Phi(\alpha) = [\phi_1(\alpha) , \dots , \phi_n(\alpha)]$$ *Basis functions (sinusoids, exponentials, polynomial (trend))*

$$\hat{y}(\alpha) = \Phi(\alpha)\, b \qquad r(\alpha) = y - \hat{y}(\alpha) \Longrightarrow b = \Phi(\alpha)^{\dagger} y$$

$$\min_{\alpha} \tfrac{1}{2} \| r(\alpha) \|_2^2 = \min_{\alpha} \tfrac{1}{2} \| (I - \Phi(\alpha)\Phi(\alpha)^{\dagger})\, y \|_2^2$$

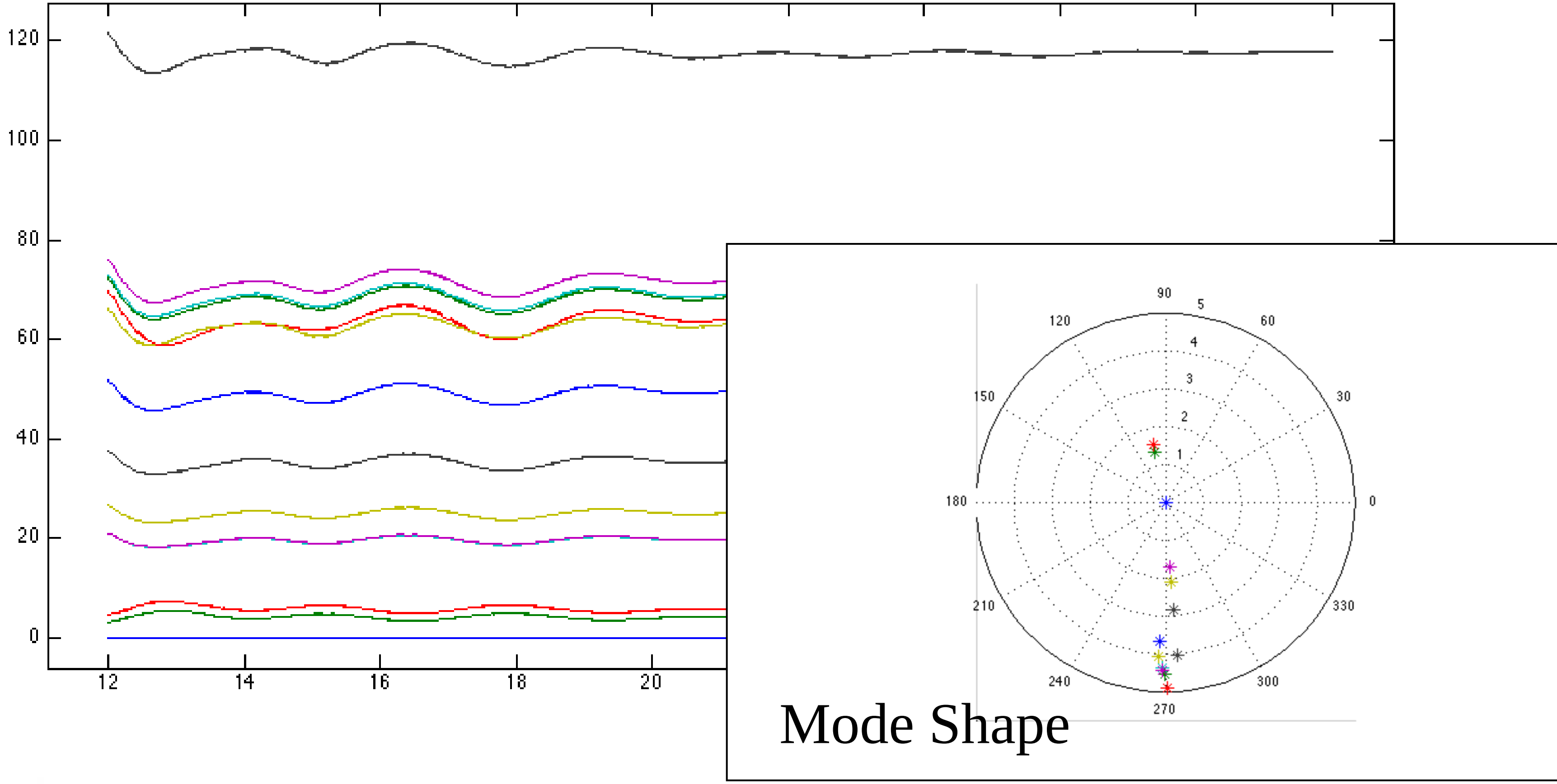
- Variable Projection Method
  - *"The Differentiation of Pseudo-Inverses and Nonlinear Least Squares Problems Whose Variables Separate,"* Golub and Pereyra (1973)

<u>*Gradient*</u>: $$\nabla \tfrac{1}{2} \| r(\alpha) \|_2^2 = J^T r(\alpha) \qquad J = \left[\frac{\partial r(\alpha)}{\partial \alpha_1} \ \cdots \ \frac{\partial r(\alpha)}{\partial \alpha_p} \right]$$

$$\frac{\partial r(\alpha)}{\partial \alpha_j} = -\left[\left(P^{\perp} \frac{\partial \Phi(\alpha)}{\partial \alpha_j} \Phi(\alpha)^{-} \right) + \left(P^{\perp} \frac{\partial \Phi(\alpha)}{\partial \alpha_j} \Phi(\alpha)^{-} \right)^{\mathrm{T}} \right] y \qquad P^{\perp} = I - \Phi(\alpha)\, \Phi^{\dagger}(\alpha)$$

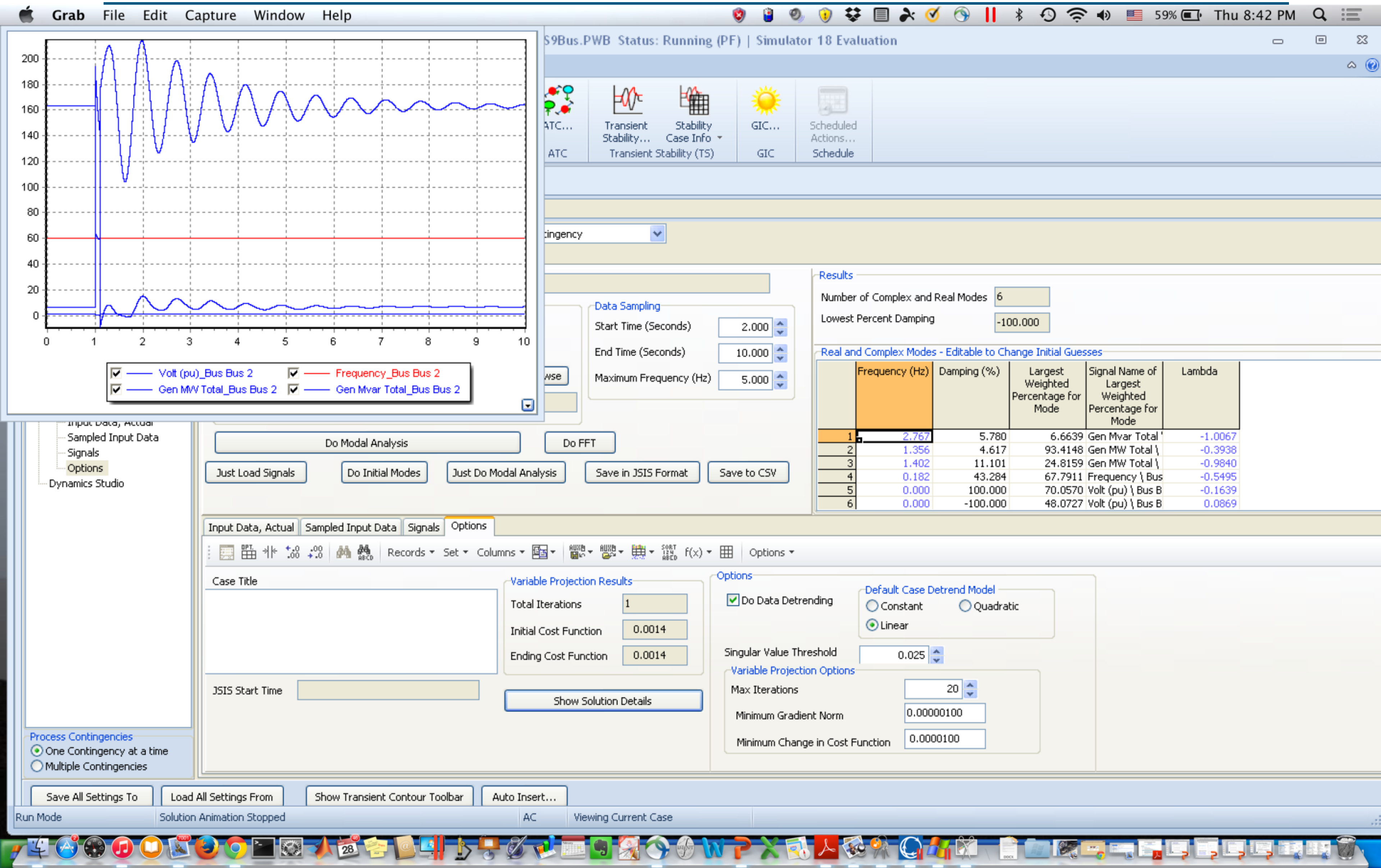
Sample Results

Compare data and Ringdown Tool fit.



Mode Shape

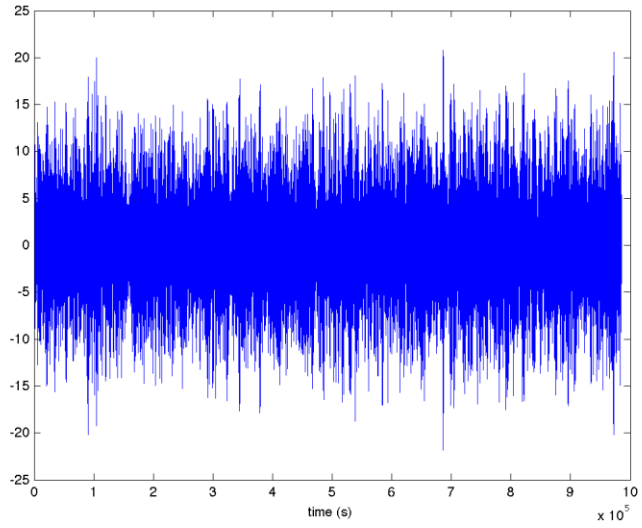
PowerWorld Transient Simulator



	Frequency (Hz)	Damping (%)	Largest Weighted Percentage for Mode	Signal Name of Largest Weighted Percentage for Mode	Lambda
1	2.767	5.780	6.6639	Gen Mvar Total '	-1.0067
2	1.356	4.617	93.4148	Gen MW Total \	-0.3938
3	1.402	11.101	24.8159	Gen MW Total \	-0.9840
4	0.182	43.284	67.7911	Frequency \ Bus	-0.5495
5	0.000	100.000	70.0570	Volt (pu) \ Bus B	-0.1639
6	0.000	-100.000	48.0727	Volt (pu) \ Bus B	0.0869

Ambient Data Analysis

- The goal of this work is to estimate oscillatory modes by examining ambient (noisy) data.



Illustrative Example (simulation)

How can we estimate modes from this data? Using curve fitting?

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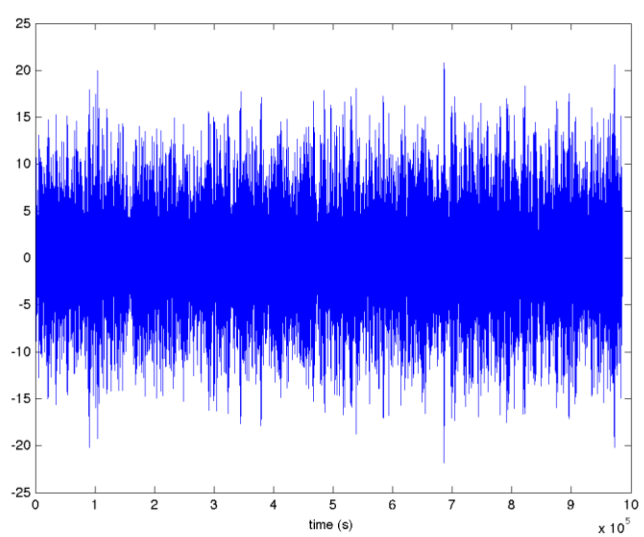
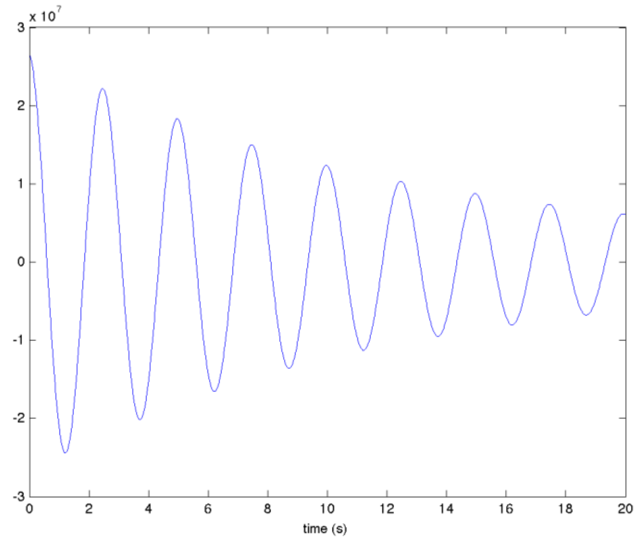
Ambient Data Analysis

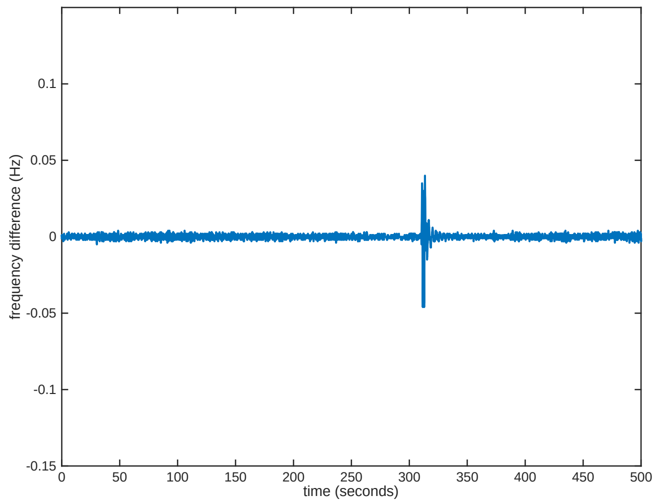
- Calculate Sample Autocorrelation. Perform curve fitting (VARPRO) on this.

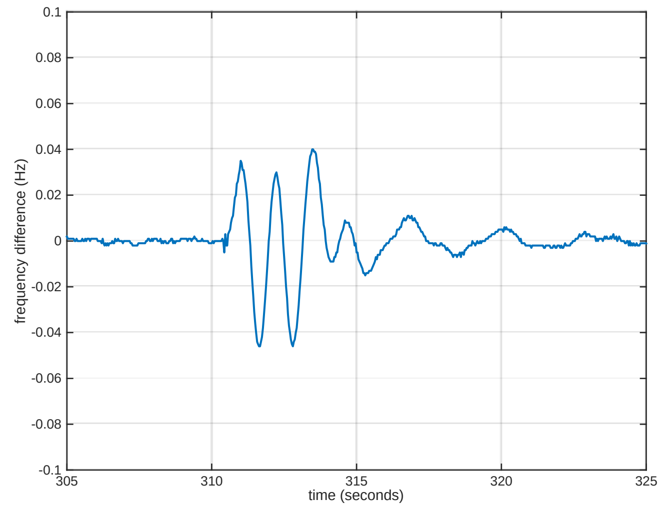




Modal frequency and damping correctly identified:
0.4 Hz at 3% damping. (0.4002 Hz and 2.98% calculated)

PMU Data Analysis: Ringdown



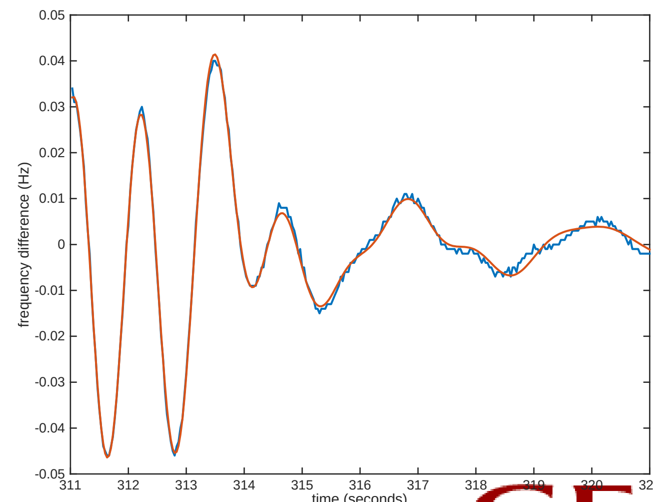


Ringdown Analysis (varpro)

0.32 Hz @ 9% damping

0.67 Hz @ 13 % damping

0.87 Hz @ 10 % damping



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Ambient Data

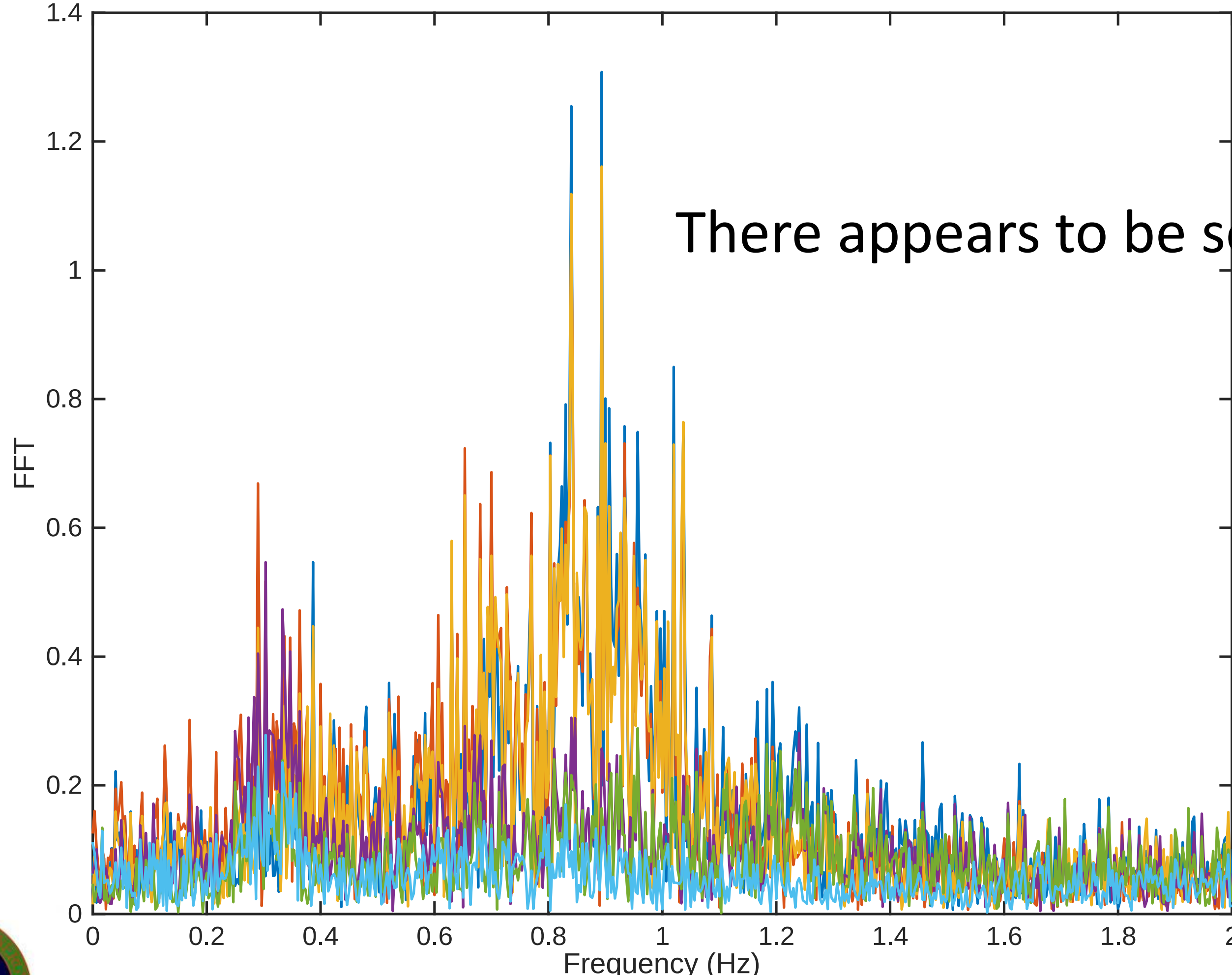
Use five minutes of data prior to disturbance to estimate modes:

Is there any information there? (FFT)

Estimate modes using

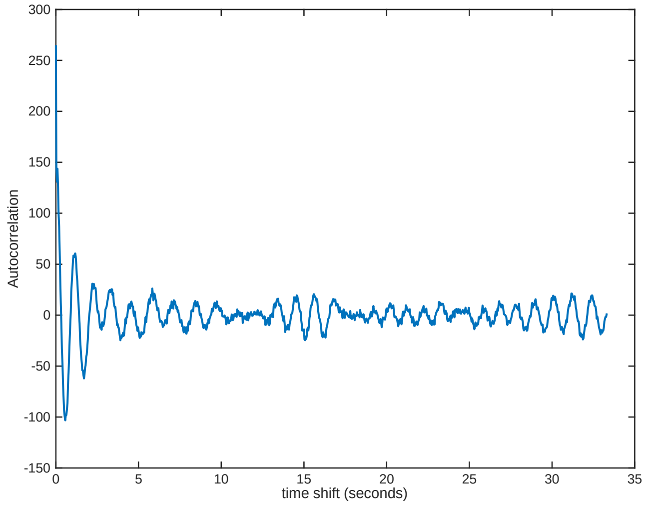
- Yule-Walker (model fitting)
- Varpro analysis of sample autocorrelations (curve fitting)

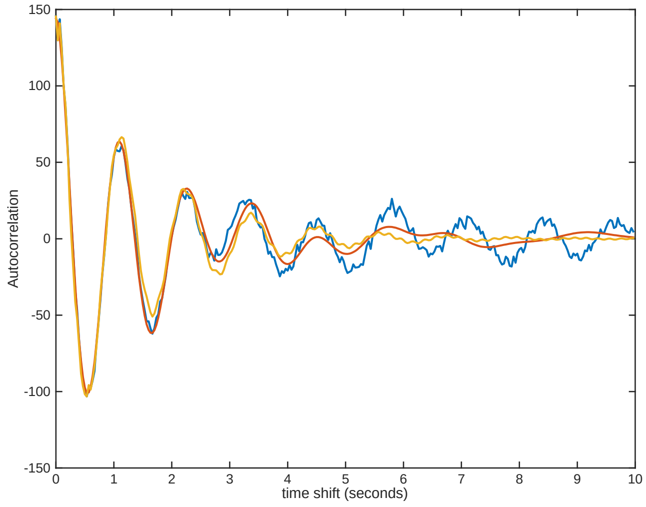
Ambient Data: FFT



There appears to be some information

Autocorrelation Fit (Varpro)





Ringdown Analysis (varpro)

0.32 Hz @ 8% damping
1.20 Hz @ 7 % damping
0.87 Hz @ 11 % damping

Decent fit at start.

Yule-Walker

0.89 Hz @ 12 % damping
+ others

Promising start …

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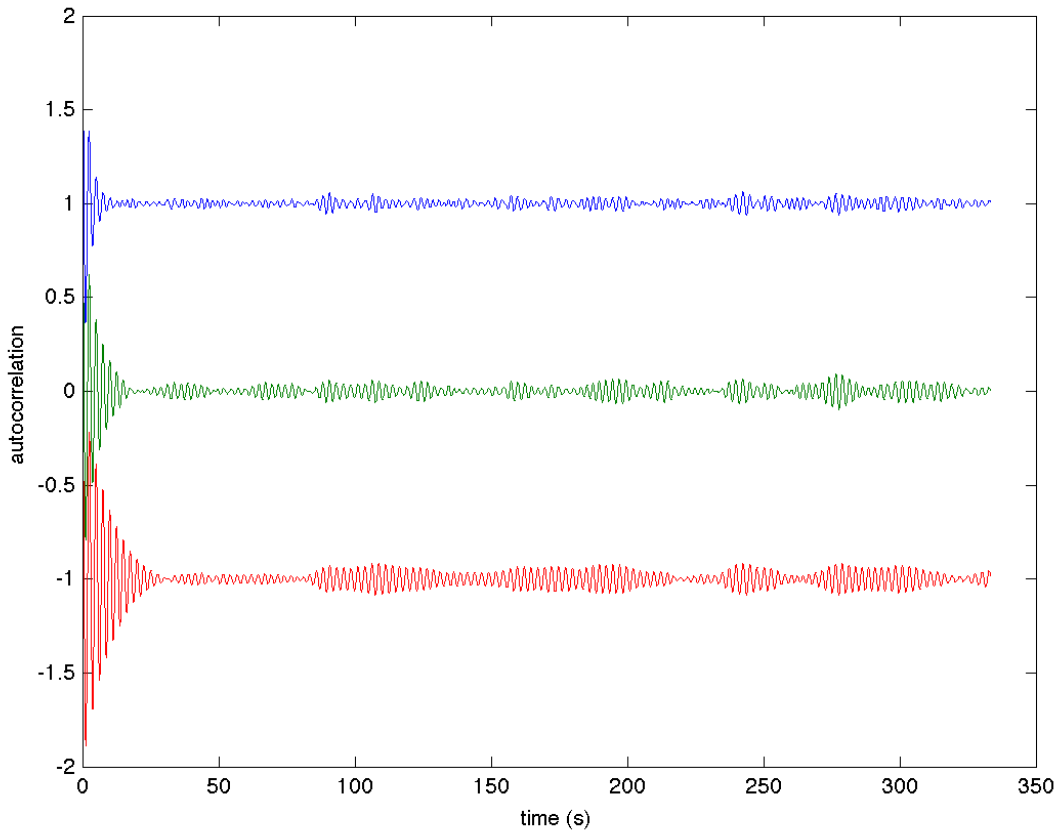
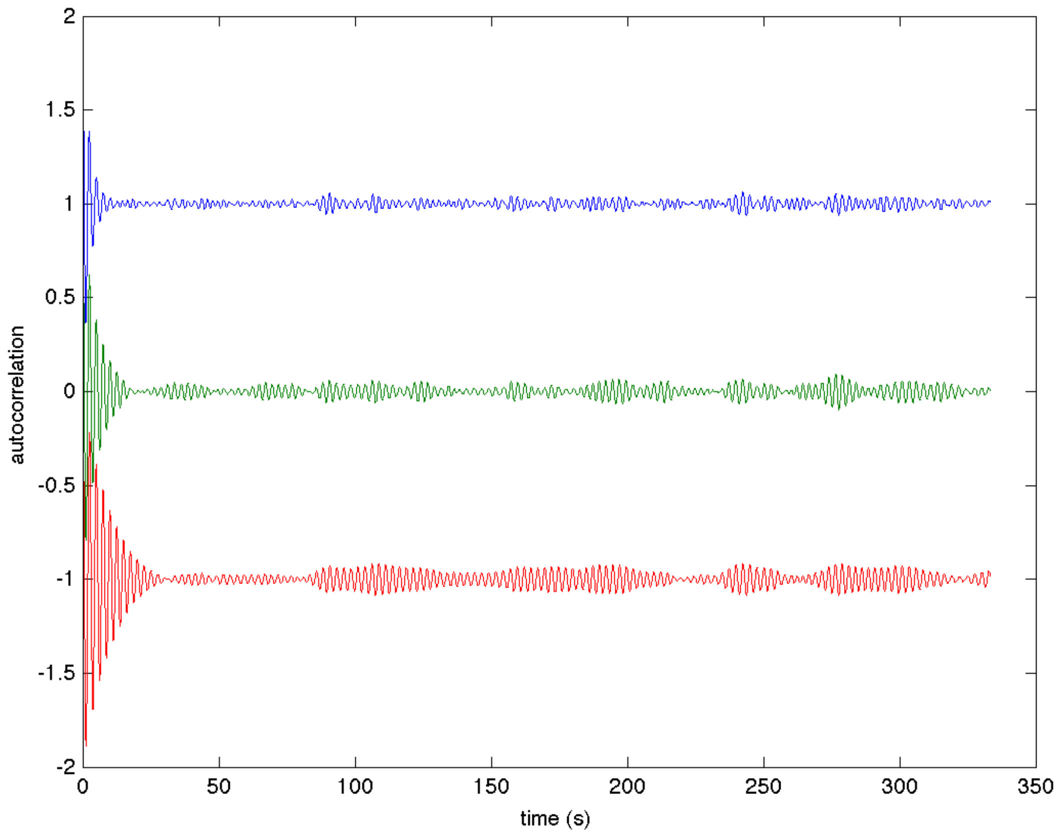
Autocorrelation Steady-State Metric



Autocorrelation of three systems with different dampings: 16%, 8%, and 4%.

Qualitatively, the effects of damping are noticeable in the steady state characteristic.

Autocorrelation Steady-State Metric



Consider using this information:

A. Calibrate to known damping characteristics to estimate damping.

A. Introduce new metric related to steady-state autocorrelation characteristic.

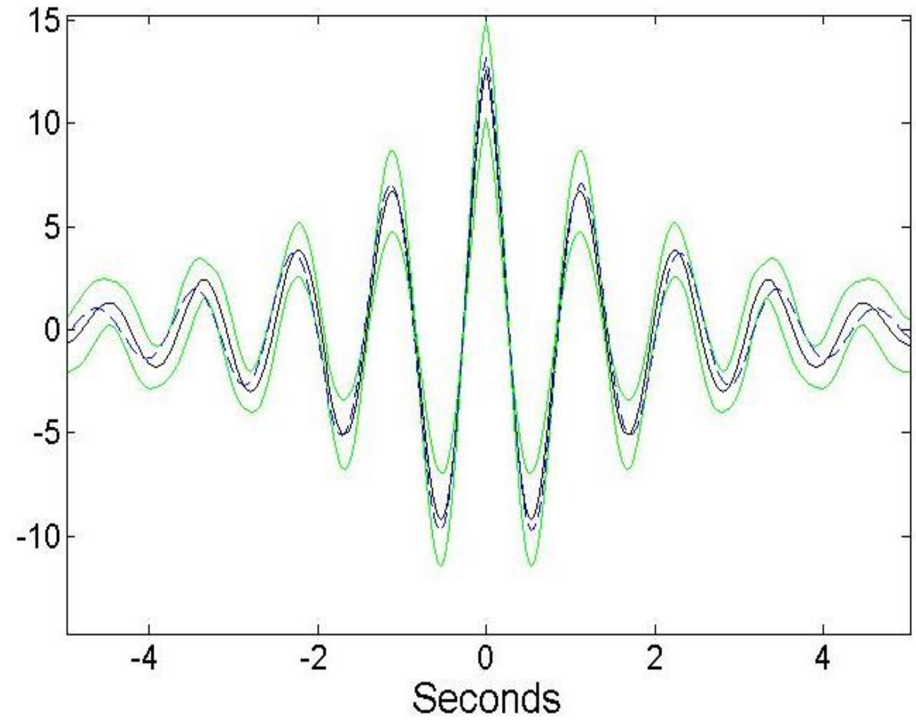
Data-Based Error Bounds

- Goal: find error bounds on modal-parameter estimates.

- Why?
  - Give confidence intervals.
  - Understand how much ambient data is needed.
  - Adapt algorithm as needed.

- How?
  - Data-only approach:
    1. Find error statistics for the sample autocorrelation.
    2. Bound estimates as found by curve-fitting algorithm

- Example based on synthetic data.



damping-ratio estimate: (10 ± 1.1)%

Research for 2015/2016

1. Analyze more data sets. BPA brake data

2. Examine information in steady-state sample autocorrelation curve.

3. Statistical Error Analysis: to estimate error bounds on estimates. Work in cooperation with Sandip Roy of Washington State University.

4. Implement Algorithms in BPA on-line test facility.